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6. AUTHOR(S)
A.V. Oppenheim, A. Baggeroer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

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Annual Report for Office of Naval Research
Adaptive Array Processing in Uncertain Inhomogeneous Media

Final Report

Co-Investigators: **Alan V. Oppenheim**
Massachusetts Institute of Technology
Research Laboratory of Electronics
50 Vassar Street, 36-615
Cambridge, MA 02139
Tel.: (617) 253-4177

Arthur Baggeroer
Massachusetts Institute of Technology
Research Laboratory of Electronics
50 Vassar Street, 36-615
Cambridge, MA 02139
Tel.: (617) 253-5287

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This report summarizes the effort performed under the grant "Adaptive Array Processing in Uncertain Inhomogeneous Media". The format principally consists of a compilation of theses, presentations, reports and peer reviewed journal articles with the text of their abstracts. The full texts have been sent to the program manager as published. Several research efforts continue beyond the expiration of this grant.

Adaptive array processing has been an active research area in radar and to a lesser extent in sonar. The emphasis of much of this research concerned robust matched field processing. In this context the most extensive review article on this topic was written. It was first published in a NATO ASI Proceedings and will soon appear in a special issue on Sonar Signal Processing in the *Journal of Oceanic Engineering.* A new approach based upon minmax methods was also developed by Preisig in his doctoral thesis. Most approaches to environmental mismatch desensitize the correlation replica signal whereas this approach examines minimizes the maximum mismatch with a region. More general array, or multisensor work, for signal enhancement for uncertain systems was also published.

Ongoing work concerns robust matched field methods for media where the modes decorrelate and establishing bounds on matched field performance. The coherence issue is particularly relevant to higher frequency and shallow water propagation where the medium has more variablitity and modes tend to couple more. The performance bounds resulted from the review article. We were impressed that many algorithms had been proposed but there was no systematic way to place lower bounds on their performance. Since many involved uncertain environments, we extended earlier work to provide Cramer Rao bounds for uncertain environments. This is relevant to sonars which combine tomography for estimating the environmental uncertainties with source localization.

Peer Reviewed Publications

0.1 Accepted

[1] A.B. Baggeroer, W.A. Kuperman, and P.N. Mikhalevsky, "An Overview of Matched Field Methods in Ocean Acoustics" an invited article to appear in *IEEE Journal on Oceanic Engineering: Special Issue on Sonar Signal Processing*, October 1993.

> Recent array processing methods for ocean acoustics have utilized the physics of wave propagation as an integral part of their design. The physics of the propagation leads to both improved performance and to algorithms where the complexity of the ocean environment can be exploited in ways not possible with traditional plane wave based methods. These methods based upon solutions of the wave equation have become known as matched field methods. Matched field processing (MFP) is a generalized beamforming method which uses the spatial complexities of acoustic fields in an ocean waveguide to localize sources in *range*, *depth* and *azimuth* or to infer parameters of the waveguide itself. It has experimentally localized sources and accuracies exceeding the Rayleigh limit for depth and the Fresnel limit for range by two orders of magnitude. MFP exploits the coherence of the mode/multipath structure and it is especially effective at low frequencies where the ocean supports coherent propagation over very long ranges. This contrasts with plane wave based models which are degraded by model and multipath phenomena and are generally ineffective when waveguide phenomena are important. MFP is a spatial matched filter where the correlation signal, or replica, is determined by the Green's function of the waveguide. It can have either conventional or adaptive for-

mulations and it has been implemented with an assortment of both narrowband and wideband signal models. All involve some form of correlation between the replicas derived from the wave equation and the data measured at an array of sensors. since the replica generally has a complicated dependence upon the source location and environmental parameters, the wave equation must be solved over this parameter space. One can view MFP as an inverse problem where one attempts to invert for these dependencies over the theoretical aspects of MFP and this is supported by numerous simulations; several experiments acquiring data for MFP now have been conducted in several ocean environments and these have demonstrated both its capabilities and some of its limitations. Consequently, there is a modest understanding of both the theory and the experimental capabilities of MFP.

[2] J.R. Buck and P.L. Tyack, "A Quantitative Measure of Similarity for Tursiops Truncatus Signature Whistles," to appear in *Journal of the Acoustical Society of America.*

Bottlenose dolphins (*Tursiops Truncatus*) are believed to produce individually distinctive narrowband "signature whistles." These whistles may be differentiated by the structure of their frequency contours. An algorithm is presented for extracting frequency contours from whistles and comparing two such contours. This algorithm performs non-uniform time-dilation to align contours and provides a quantitative distance measure between contours. Results from two recognition experiments using the algorithm on recorded dolphin whistles are presented

[3] J. Preisig, "A Minmax Approach to Adaptive Matched Field Processing in an Uncertain Propagation Environment," to appear in *IEEE Transactions on Signal Processing.*

Adaptive array processing algorithms have achieved widespread use because they are very effective at rejecting unwanted signals (i.e., controlling sidelobe levels) and in general have very good resolution (i.e., have narrow mainlobes). However, many adaptive high-resolution array processing algorithms suffer a significant degradation in performance in the presence of environmental mismatch. This sensitivity to environmental mismatch is of particular concern in problems such as long-range acoustic array processing in the ocean where the array processor's knowledge of the propagation characteristics of the ocean is imperfect. An Adaptive Minmax Matched Field Processor is formulated which combines adaptive matched field processing and minmax approximation techniques to achieve the effec-

tive interference rejection characteristic of adaptive processors while limiting the sensitivity of the processor to environmental mismatch. An efficient implementation and alternative interpretation of the processor are developed. The performance of the processor is analyzed using numerical simulations.

[4] E. Weinstein, M. Feder and A.V. Oppenheim, "Multi-Channel Signal Separation by Decorrelation," to appear in *IEEE Transactions on Signal Processing*, August, 1993.

In a variety of contexts observations are made of the outputs of an unknown multiple-input multiple-output linear system, from which it is of interest to identify the unknown system and to recover the input signals. This often arises, for example, with speech recorded in an acoustic environment in the present of background noise or competing speakers, in passive sonar applications, and in data communications in the presence of cross-coupling effects between the transmission channels. In this paper we specifically consider the two-channel case in which we observe the outputs of a 2x2 linear time invariant system. Our approach consists of reconstructing the input signals by assuming that they are statistically uncorrelated, and imposing this constraint on the signal estimates. In order to restrict the set of solutions, additional information on the true signal generation and/or on the form of the coupling systems is incorporated. Specific algorithms are developed and demonstrated for the case in which the coupling systems are discrete-time causal finite impulse response (FIR) filters. As a special case, the proposed approach suggests a potentially interesting modification of Widrow's least squares method for noise cancellation, when the reference signal contains a component of the desired signal.

[5] E. Weinstein, A.V. Oppenheim, M. Feder and J.R. Buck, "Iterative and Sequential Algorithms for Multi-Sensor Signal Enhancement", to appear in *IEEE Transactions on Signal Processing*, March, 1994.

In problems of enhancing a desired signal in the presence of noise, multiple sensor measurements will typically have components from both the signal and the noise sources. When the systems that couple the signal and the noise to the sensors are unknown, the problem becomes one of joint signal estimation and system identification. In this paper we specifically consider the two-sensor signal enhancement problem in which the desired signal is modeled as a Gaussian autoregressive (AR) process, the noise is modeled as a white Gaussian process, and the coupling systems are modeled as linear time-invariant

finite impulse response (FIR) filters. Our primary approach consists of modeling the observed signals as outputs of a stochastic dynamic linear system, and we apply the Estimate-Maximize (EM) algorithm for jointly estimating the desired signal, the coupling systems, and the unknown signal and noise spectral parameters. The resulting algorithm can be viewed as the time-domain version of our previously suggested frequency-domain approach, where instead of the noncausal frequency-domain Weiner filter we use the Kalman smoother. This time-domain approach leads naturally to a sequential/adaptive algorithm by replacing the Kalman smoother with the Kalman filter, and in place of successive iterations on each data block the algorithm proceeds sequentially though the data with exponential weighting applied to allow adaption to nonstationary changes in the structure of the data. A computationally efficient implementation of the algorithm is developed by exploiting the structure of the Kalman filtering equations. An expression for the log-likelihood gradient based on the Kalman smoother/filter output is also developed and used to incorporate efficient gradient-based algorithms in the estimation process.

Presentations and Conference Proceedings

[1] A.B. Baggeroer and W.A. Kuperman, "Matched Field Processing in Ocean Acoustics," an invited lecture at the NATO - Advanced Study Institute, *Proceedings of Signal Processing and Ocean Acoustics*, Maderia, Portugal, July, 1992.

Matched field processing (MFP) is a generalized beamforming method which uses the spatial complexities of acoustic fields in an ocean waveguide to localize sources in *range, depth* and *azimuth* or to infer parameters of the waveguide itself. It has localized sources with accuracies exceeding the Rayleigh limit for depth and the Fresnel limit in range by two orders of magnitude. MFP exploits the coherence of the mode/multipath structure and it is especially effective at low frequencies were the ocean supports coherent propagation over very long ranges. This contrasts to planewave based models which are degraded by model and multipath phenomena and are generally ineffective when waveguide phenomena are important. MFP is a spatial matched filter where the correlation signal, or replica, is determined by the Green's function of the waveguide. It c an have either conventional or adaptive formulations and has been implemented with an assortment of both narrowband and wideband signal models. All involve some form of correlation between replicas

derived from the wave equation for the impulse response and the data measured at an array of sensors. Since this impulse response generally has a complicated dependence upon the source location and environmental parameters, the wave equation must be solved over the parameter space. One can view MFP as an inverse problem where one attempts to invert for these dependencies over the parameter space of the source and the environment. There is currently a large literature discussing many theoretical aspects of MFP and supported by lots of simulations; a considerable number of experiments acquiring data for MFP now have been conducted in several ocean environments. Consequently, there is a modest understanding of both the theory and the experimental capabilities of MFP. This article provides an overview of both.

[2] J. Jachner and H. Lee, "Cramer-rao bounds on direction estimates of closely spaced emitters in multi-dimensional applications", *1992 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. 2, pp. 513-516, (San Francisco, CA), March 1992.

The main results of this paper are characteristic of the Cramer-Rao (CR) bound on the variance of direction estimates for closely-spaced emitters in multiple parameter (multi-D) scenarios. Specifically, simple analytic expressions for the CR bound are presented for co-linear emitter configurations, which show the bound to be very *sensitive to the maximum spacing between emitters* ($\delta\omega$). Results also are cited for CR bound sensitivity to $\delta\omega$ for emitter configurations in which the emitters are not co-linear. The latter results exhibit greatly reduced sensitivity to the direction separation factor $\delta\omega$. Thus the results show that *degeneracies are present in multi-D parameter estimation scenarios that are not present in 1-D scenarios.* Specifically emitter resolution and direction estimation can be expected to be much more challenging for some emitter configuration than for others. The case of co-linear emitters appears to be a particularly stressful one.

[3] A.B. Baggeroer and H. Schmidt, "Parameter Estimation Bounds on Estimating Geophysical Parameters Using Matched-Field Tomography," invited lecture in the Spring 1993 Acoustical Society of America Conference, (Ottawa) Canada, May 21, 1993, *Journal of the Acoustical Society* Vol.93, No. 4, Part 2, April 1993.

Matched-field tomography uses full wave modeling to infer geophysical parameters of the propagation medium. As such, it is fundamentally a problem in estimation theory. The signal processing literature has long used bounding methods to establish performance

limitations and identify coupling among estimates of a set of parameters. The most extensive of these is the Cramer-Rao bound, which has been applied to the source localization problem for matched-field processing. The Cramer-Rao, as well as other bounds for analyzing the sidelobe, or ambiguity, problem can be applied to matched-field tomography. These will be derived and applied to problems in identifying the sound-speed profile and elastic properties of the sea floor.

[4] J.C. Preisig, "Optimal Minmax Estimation and the Development of Minmax Estimation Error Bounds," *IEEE International Conference on Acoustics, Speech, and Signal Processing*, Vol. 5, pp. 285-288, (San Francisco, CA), March 1992.

> It is often desired to create an optimal estimator of some parameter θ given the observation x. However, the relationship between θ and x may depend on another parameter ϕ which is unknown to the processor and not of direct interest. In this case, an estimator which performs well for one value of ϕ may perform poorly for another value of ϕ. One approach to dealing with this problem is to develop an estimator whose worst case performance evaluated over some range of ϕ is as good as possible. Such an optimal minmax estimator is derived. The derivation of this estimator also motivates an approach to developing lower bounds on the minmax estimation error achievable by any estimator.

Technical Reports

[1] J.C. Preisig, "Adaptive Matched Field Processing in an Uncertain Propagation Environment," RLE Tech. Rep. 567, M.I.T., Cambridge, MA, January 1992.

> Adaptive array processing algorithms have achieved widespread use because they are very effective at rejecting unwanted signals (i.e., controlling sidelobe levels) and in general have very good resolution (i.e., have narrow mainlobes). However, many adaptive high-resolution array processing algorithms suffer a significant degradation in performance in the presence of environmental mismatch. This sensitivity of environmental mismatch is of particular concern in problems such as long-range acoustic array processing in the ocean where the array processor's knowledge of the propagation characteristics of the ocean is imperfect. An Adaptive Minimax Matched Field Processor has been developed which combines adaptive matched field processing and minmax approximation techniques to achieve

the effective interference rejection characteristic of adaptive processors while limiting the sensitivity of the processor to environmental mismatch.

This derivation of the algorithm is carried out within the framework of minmax signal processing. The optimal array weights are those which minimize the maximum conditional mean squared estimation error at the output of a linear weight-and-sum beamformer. The error is conditioned on the propagation characteristics of the environment and the maximum is evaluated over the range of environmental conditions in which the processor is expected to operate. The theorems developed using this framework characterize the solutions to the minmax array weight problem and relate the optimal minmax array weights to the solution to a particular type of weiner filtering problem. This relationship makes possible the development of an efficient algorithm for calculating the optimal minmax array weights and the associated estimate of the signal power emitted by a source at the array focal point. An important feature of this algorithm is that it is guaranteed to converge to an exact solution for the array weights and estimated signal power in a finite number of iterations.

The Adaptive Minmax Matched Field Processor can also be interpreted as a two-stage Minimum Variance Distortionless Response (MVDR) Matched Field Processor. The first state of this processor generates an estimate of the replica vector of the signal emitted by a source at the array focal point, and the second stage is a traditional MVDR Matched Field Processor implemented using the estimate of the signal replica vector.

Computer simulations using several environmental models and types of environmental uncertainty have shown that the resolution and interference rejection capability of the Adaptive Minmax Matched Field Processor is close to that of a traditional MVDR Matched Field Processor which has perfect knowledge of the characteristics of the propagation environment and far exceeds that of the Bartlet Matched Field Processor. In addition, the simulations show that the Adaptive Minmax Matched Field Processor is able to maintain it's accuracy, resolution and interference rejection capability when it's knowledge of the environment is only approximate, and is therefore much less sensitive to environmental mismatch than is the traditional MVDR Matched Field Processor

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